Time resolved 3-D mapping of atmospheric aerosols and clouds during the recent Atmospheric Radiation Measurement water vapor Intensive Operating Period

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ABSTRACT

We have developed simplified conical scanning telescopes using Holographic Optical Elements (HOEs) to reduce the size, mass, angular momentum, and cost of scanning lidar systems. This technology enables wide-angle scanning and three-dimensional measurements of atmospheric backscatter when used in airborne instruments, and high temporal and spatial resolution observations of atmospheric dynamic structure, including wind profiles from ground-based facilities. We deployed the Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE) on the ground at the Department Of Energy's (DOE) central site in northern Oklahoma during their most recent Atmospheric Radiation Measurement (ARM) program Water Vapor Intensive Operating Period (WVIOP) in September-October 2000, in order to take advantage of the many coincident atmospheric measurements taking place at that time while collecting data with which to develop data reduction algorithms. We are evaluating the HARLIE technology and scanning techniques with an eye toward their application into other types of lidar systems, including Raman and Doppler lidar systems.

Keywords: lidar, backscatter, atmospheric aerosols, clouds, holographic optical element, scanning, atmospheric dynamics, Doppler, wind profiles

1. INTRODUCTION

Lidar remote sensing instruments can make a significant contribution to satisfying many of the required measurements of atmospheric and surface parameters for future spaceborne platforms, including topographic altimeters, atmospheric profiles of, wind, humidity, temperature, trace molecules, aerosols, and clouds. It is highly desirable to have wide measurement swaths for rapid coverage rather than just the narrow ribbon of data that is obtained with a nadir only observation. For most applications global coverage is required, and for wind measurements scanning or pointing is required in order to retrieve the full 3-D wind vector from multiple line-of-sight Doppler measurements. Conventional lidar receivers make up a substantial portion of the instrument's size and weight. Wide angle scanning typically requires a large scanning mirror in front of the receiver telescope, or pointing the entire telescope and aft optics assembly. Either of these methods entails the use of large bearings, motors, gearing and their associated electronics. Spaceborne instruments also need reaction wheels to counter the angular momentum imposed on the spacecraft by these motions.

Holographic scanning lidar is a new technology for replacing large aperture scanning telescope systems with lighter, less costly, and simpler optical mechanisms. This is seen as an enabling technology for the eventual use of scanning lidars in spaceborne Earth remote sensing instruments. It is based on the use of large HOEs to collimate and transmit laser light as well as collect and focus atmospheric backscatter while scanning in a conical pattern.[1-5] Conical scanning is perhaps the most efficient means of obtaining multiple look angles and cross track coverage. There are many applications, especially topographic mapping, 3-D atmospheric dynamics based on monitoring the motions of atmospheric aerosol and cloud structures[6], and wind profiling based on these motions[7] or by combining the holographic scanning telescope with a Doppler lidar receiver. There can be significant cost advantages to using holographic scanning lidar telescopes over conventional reflective scanning lidar telescopes in ground based, airborne, and spaceborne applications. Scanning an HOE telescope is both easy and practical to use in the visible and near IR. While it is difficult to achieve diffraction limited performance in HOEs, they can be used to simplify an optical system design and layout, requiring fewer optical and mechanical components, hence lowering costs. HOEs are also very inexpensive to reproduce. Once a master HOE is made for a particular design, it is

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easy to reproduce using a contact copy process, in a manner similar to making multiple photographic prints from a single negative.

2. OBJECTIVES

During previous field experiments involving HARLIE[8] ground-based measurements in concert with a zenith wide-angle video camera (SKYCAM), the Army Research Office Lidar (AROL), and the Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing[9] (PHASERS) we developed methods for obtaining wind profiles from HARLIE data and from the SKYCAM video recordings combining with AROL measured cloud altitudes.[6, 7, 10] The objectives for deploying HARLIE in the WVIOP were to test a new trailer configuration for ground based deployments, acquire data sets with coincident rawindsondes for validating our wind profile algorithms, and to obtain simultaneous Raman lidar measurements for transferring absolute backscatter calibration information.

3. INSTRUMENTS

HARLIE was the second holographic scanning lidar, and built primarily as an airborne demonstration using a 1064 nm wavelength laser. It was completed in 1997, and flown in a series of engineering flights in 1998. Because there are no photosensitive dyes that absorb sufficiently at 1064 nm, the transmission HOE for HARLIE was produced at a wavelength of 488 nm. Special techniques were developed to compensate for the large aberrations that are normally induced when using an HOE at a wavelength far removed from its construction wavelength[11]. Figure 1 is a photo of the HARLIE instrument being tested on the ground looking up. The 40 cm diameter HOE is mounted in a large ring ball bearing on the top of the transceiver box, and the laser and detector are mounted on the bottom. The HOE spins by means of a belt driven by a small motor mounted on the side. The transmitted laser beam is expanded to 5 cm diameter before it passes through the HOE, which collimates and diffracts the beam at a 45-degree angle. A small turning mirror used to introduce the laser beam onto the HOE's optical axis obscures the central portion of the HOE. The remainder of the HOE area is used to collect the atmospheric backscatter and focus it into a 200-micron diameter optical fiber located at the focal distance of 102 cm. The fiber delivers the light to an optics package containing a 500 pm interference filter and a photon-counting Geiger-mode avalanche photodiode detector. The average diffraction efficiency of the entire HOE area is 85%.

The electronics rack contains the data system, laser power supply and laser chiller. The laser is a compact Nd:YAG transmitting 1-mJ Q-switched pulses at a 5 KHz repetition rate. HARLIE is capable of scan speeds of up to 30 rpm, but we normally use a scan rate of 1.67 rpm (10 degrees/sec) for ground based measurements in order to enhance our azimuthal spatial resolution. Using 100 ms integration times gives us an atmospheric profile for every 1-degree in azimuth. The range resolution is 30 meters, corresponding to 20 meters in altitude resolution for the 45-degree fixed elevation angle.

For the ARM WVIOP 2000 deployment, we installed HARLIE in a small trailer (Figure 2) measuring 210 cm wide, 420 cm long, and 210 cm high (excluding wheels and axles). Installed in the rear of the trailer, HARLIE is positioned so the HOE is facing up and only a few centimeters from a transmitting window in the roof. The forward portion of the trailer houses the electronics rack and a desk and workspace for an operator, if required. The entire system can be set up after transporting to the deployment site in about one hour. The SKYCAM was set up outside the trailer on a tripod, and being a visible-light color camera, its use was restricted to daytime, non-precipitating conditions. We did not deploy AROL during the WVIOP, so we used the cloud altitudes from the HARLIE data to combine with the angular motions of cloud features from the SKYCAM videos to generate independent cloud-tracked wind profiles. The ARM program launched rawindsondes every three hours, which we used for independent wind profile comparisons with both the HARLIE wind profiles and the SKYCAM wind profiles.

Figure 1. Photograph of the HARLIE transceiver (*left*) and electronics rack (*right*). On top of the transceiver is a 40 cm diameter transmission HOE having a 1-meter focal length.

Figure 2. Photograph of the HARLIE trailer and SKYCAM deployed at the ARM SGP CART site during the recent water vapor IOP.

4. MEASUREMENTS

The ARM Water Vapor Intensive Operating Period (WVIOP) 2000 ran from 18 September through 8 October, 2000 at the DOE Climate and Radiation Test-bed (CART) site near Lamont, Oklahoma, USA, coordinates 97.496°W, 36.61 °N. Part of the Great Plains, the area is flat, semi-arid pasture and grain farm land, intersected by a grid of dirt roads. Dust permeates the air when the wind blows, which is most of the time. Automotive activity generates dust plumes visible over several kilometers, and often seen in our lidar data. Figure 3 is a photograph of the portion of the CART site that contained several instruments deployed just for the WVIOP. From left to right: the CART Raman Lidar (permanently installed, measuring H2O & aerosol profiles), a storage shed, the University of Wisconsin Aeribago (AERI is an Infrared Michelson interferometer

Figure 3. Photograph of instruments deployed at the ARM CART site in the Southern Great Plains area in north central Oklahoma during the third Water Vapor Intensive Operating Period.

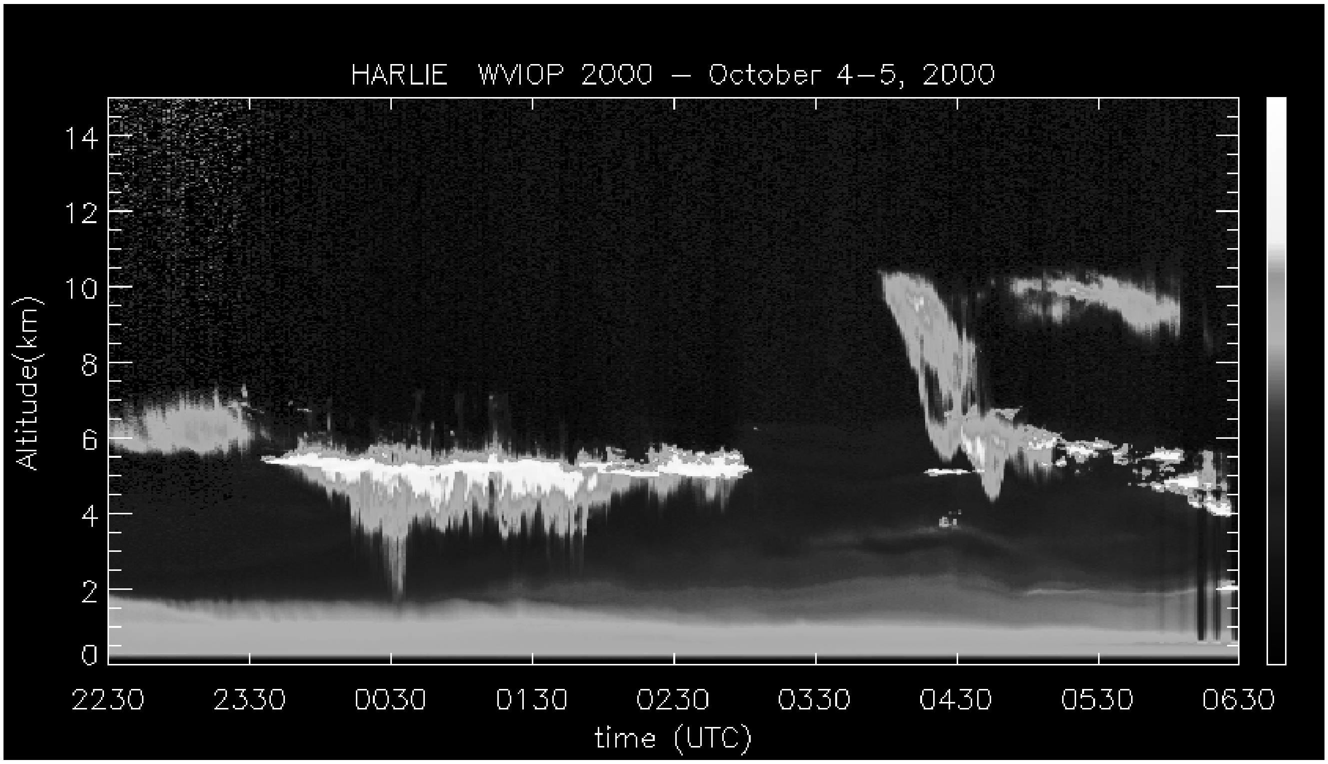

Figure 4. HARLIE backscatter profiles (scan integrated) versus time for the period 4 Oct. 2230 through 5 Oct. 0630 UT. Increasing levels of backscatter are represented by lighter shades.

measuring water vapor and temperature profiles), the Goddard Scanning Raman Lidar (the long trailer, measuring H2O and aerosol profiles), a German Water Vapor DIAL system (two short seatainers in foreground), and the HARLIE trailer.

The deployed lidars were generally run for about 8 hours a day during the IOP. HARLIE was usually used in it's scanning mode with the scan axis vertical, but twice HARLIE was put into a vertical pointing, non-scanning mode to calibrate it against Raman lidar data to get absolute backscatter using clouds. We do not use the absolutely calibrated data in order to derive wind profiles from the HARLIE data, or most other data products pertaining to the boundary layer, but will be used in the future for quantitative radiative transfer information.

HARLIE recorded over 110 hours of data on 16 days between 17 September and 6 October 2000, prior to and during the IOP, providing a unique record of time-resolved atmospheric backscatter at 1-micron wavelength. The conical scanning lidar measures atmospheric backscatter on the surface of an inverted 90 degree (full angle) cone up to an altitude of 20 km. 360-degree scans having spatial resolutions of 20 meters in the vertical and 1 degree in azimuth were obtained every 36 seconds during the daily operating period. Various boundary layer and cloud parameters are derived from the lidar data, as well as atmospheric wind vectors where there is sufficiently resolved structure in the backscatter.

Each day's HARLIE data is plotted in a 2-D time series of range-squared corrected scattering profiles by summing the data from each 360-degree scan into one profile. In this way, information on any portion of the scan is not missed, however, features tend to get smoothed and some contrast is lost. However, these plots are an excellent tool for quickly locating particular events and areas of interest, such as frontal passages, cloudy and clear periods, etc. Figure 4 is an example of the data plotted in this fashion for the period from 4 October, 2230 UT to 5 October, 0630 UT. This particular data set is rich with cloud from an occluded front that slowly passed through the area. The data series begins about one hour before sunset, the daylight evidenced by the higher noise levels that increase with altitude (due to the range-squared correction) on the left hand side of the image. Optically thin clouds are present at this time between 5.5 and 7 km altitude, changing to optically thicker clouds that appear to be capped around 5.5-6 km, and dropping (perhaps with some virga) to within 2 km of the ground. The boundary layer is marked by the region of strong aerosol scattering below 2 km at 2230, dropping to 1 km and less as the evening passes. Notice the series of waves at the top of the boundary layer between 2300 and 2400 hours. An elevated, residual aerosol layer associated with the daytime boundary layer of the cooler air mass is seen rising to the level of the clouds that occur beginning around 0430 UT. These are cirrus clouds extending up to 11 km altitude, and are probably

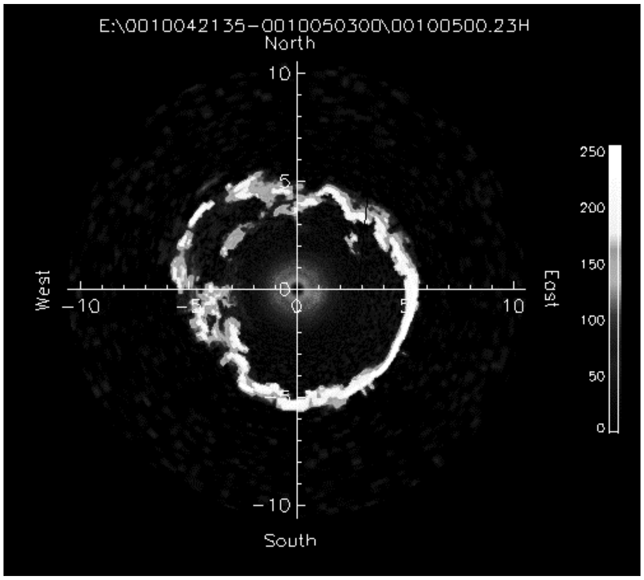

Figure 5. Polar plot of a single scan of HARLIE data for 5 October, 0023 hours UT. Optically thin clouds are present in all directions and range in altitude from 2 to 6 km.

Figure 6. A frame from the wide-angle color video camera used to record cloud activity over the region covered by the HARLIE scan.

blow-off from thunderstorms that passed northwest of the CART site. Low level cumulus clouds (around 600 m altitude) can be seen casting shadows on everything above them beginning around 0600 UT.

Another standard HARLIE data product is a series of backscatter images similar to the one just described, but with the scan azimuth angle being the X axis (for a rectilinear visualization) or alternatively, as a polar plot similar to a scanning radar display, where the radial axis represents range. For HARLIE's 45-degree elevation angle, the horizontal distance from the lidar is equal to the altitude. A time series of these images can be displayed sequentially on a computer screen as an animated sequence that can be used to help interpret atmospheric dynamic activity. Because such animated files can become quite large and unwieldy, we typically perform large amounts of averaging and data compression on them; using the MPEG file format for routine general purpose animated visualizations. Greater resolution, both temporal and spatial, can be obtained using GIF file formats for special case studies. Figure 4 is a single frame of one such visualization on a polar plot.

Videotapes of that portion of the sky encompassing the HARLIE scan were recorded using SKYCAM, a wide-angle color camera pointed toward zenith. These videos record the cloud activity over the region of the HARLIE scan and aid in the analysis of cloud dynamics. They can also be used as an independent method of obtaining wind vectors. Of course, the altitude of any clouds must be obtained from a lidar or other ceilometer, and only after the altitude of the clouds are known can the wind speed associated with the movement of those clouds be retrieved. Figure 6 is an example image from one of the SKYCAM videotapes.

5. CONCLUSIONS

The technology for using HOEs as large aperture scanning lidar telescopes is now well tested and field proven. The second such lidar to utilize this technology, HARLIE, was installed in a compact trailer and deployed during the ARM WVIOP. The trailer provided for rapid deployment and all weather operational capability. We collected over 110 hours of scanning lidar data during this campaign. Conical scanning lidar provides an effective new tool for studying atmospheric dynamics with high spatial and temporal resolution, and can provide several data products including boundary layer heights, cloud top and bottom heights, entrainment zone thickness, and horizontal wind vector profiles.

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